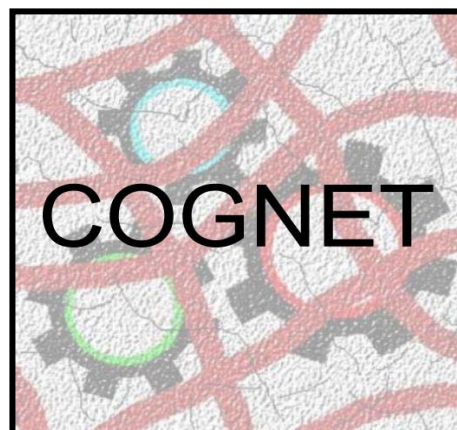


Using Bayesian Network Analysis to Support Operational Planning



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Presentation plan

- Current ADF Ops planning
 - Where does the Centre of Gravity (COG) concept fit in?
- Bayesian net representation of COG analysis
- The COG Network Effects Tool (COGNET)
 - Generic models database
 - Impact analysis tool
 - Model population
 - Model checking
 - Compiling large and complex COG networks

The essence of planning

[Barclay *et al.*, 1977] present a Decision Analysis methodology which is based on four elements:

- a set of initial courses of action,
- a set of possible consequences for each initial act,
- the value of each act in terms of money, utility or some other unit and
- the likelihood that a particular act will result in a particular consequence.

The Joint Military Appreciation Process (JMAP) considers all these issues:

“throughout course of action development the staff must consider the ‘cost-benefit’ that results in apportioning capabilities and rates of effort to achieve objectives and tasks”, and they should also “identify and analyse the consequences of potential risks and how they may impact on own and higher missions” [ADDP 5.0.1, 2002, Section 2.41]

Barclay, S., Brown, R.V., Kelly, C. III, Peterson, C.R., Philips, L.D., Selvidge, J. *Handbook for Decision Analysis*, Advanced Decision Technology Program Office of Naval Research, 1977.

The essence of military planning

- The initial stage of any military operational-level planning process (e.g. JMAP) typically includes some form of mission analysis.
- This involves identifying and analysing the superior commander's intent to determine which tasks are essential to achieve the operational objective.
- Correct assessment of the objective is deemed to be crucial to success at the operational level.
- According to current Australian Defence Force thinking:

The objective can be achieved by exploiting the enemy's centre of gravity (COG) while protecting one's own

COG/CC/CR Analysis [ADDP 5.0.1]

Centre Of Gravity:

That characteristic, capability or locality from which a military force nation or alliance derives its freedom of action, strength or will to fight at that level of conflict.

Critical Capability:

Characteristic or key element of a force that if destroyed, captured or neutralised will significantly undermine the fighting capability of the force and its centre of gravity.

Each critical capability might have a number of associated critical requirements, which are essential for it to be fully functional.

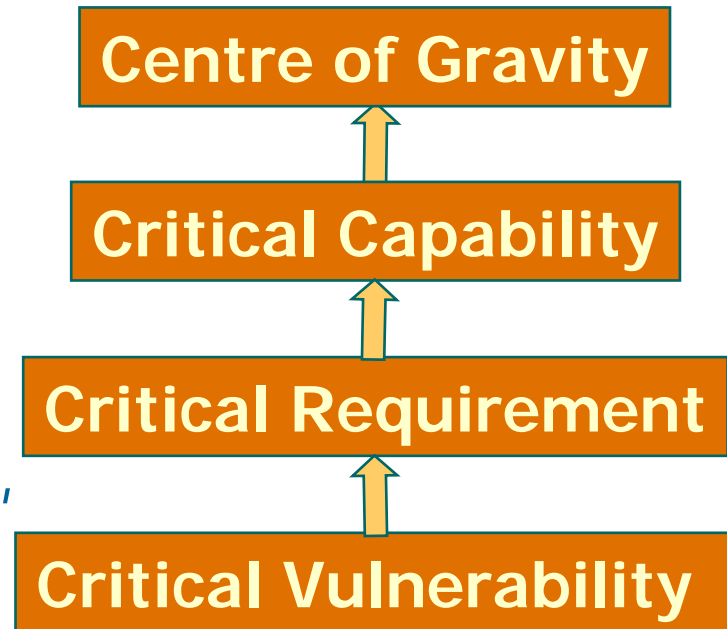
These requirements may be further decomposed into critical vulnerabilities: elements that are potentially vulnerable

Centre Of Gravity Analysis

A military COG is typically supported by a number of critical capabilities (CC)

These are in turn, supported by a number of critical requirements (CR).

Certain aspects of CC and CR are vulnerable, and called critical vulnerabilities.



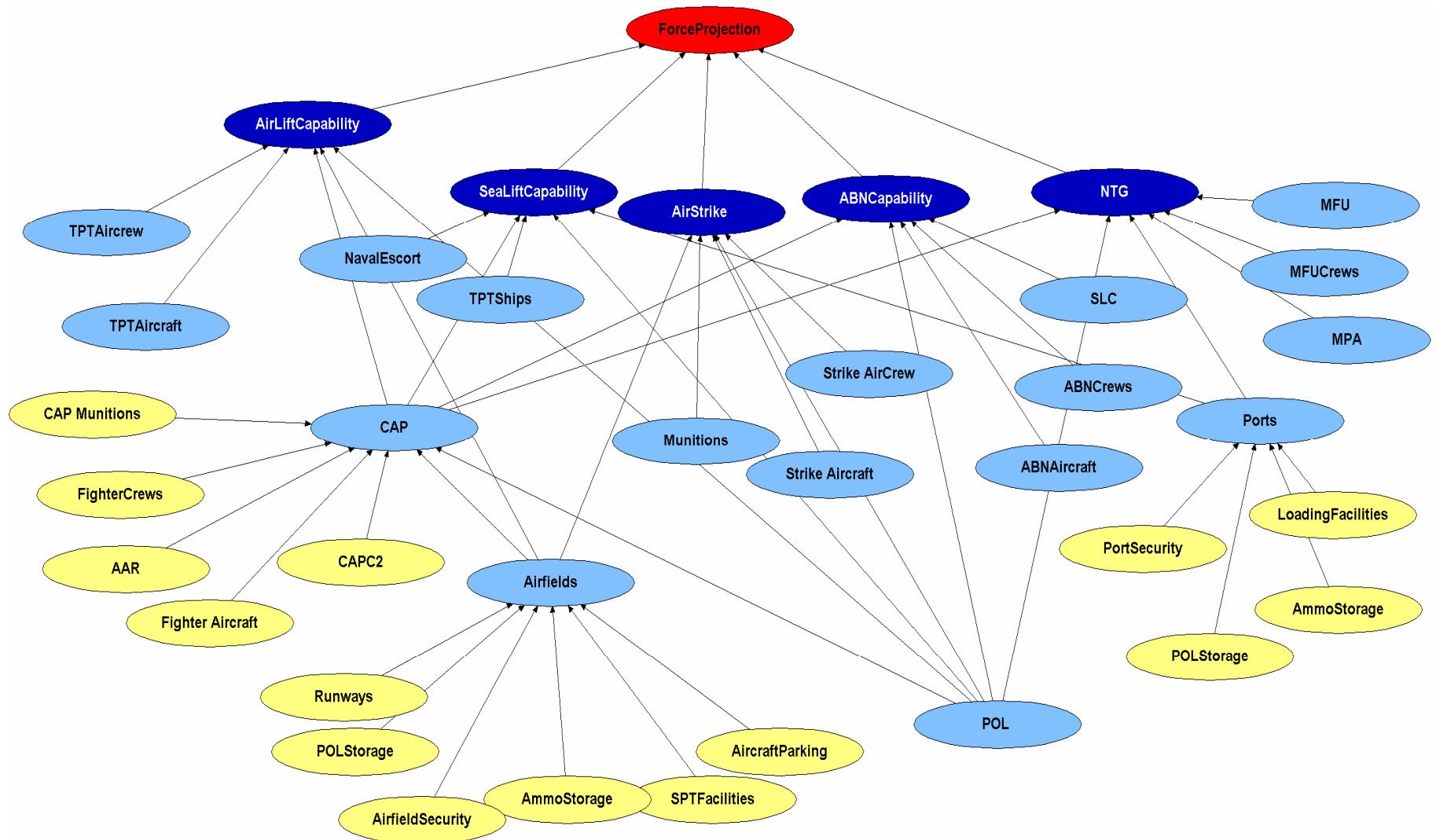
Critical Capability Matrix

C of G

Force Projection

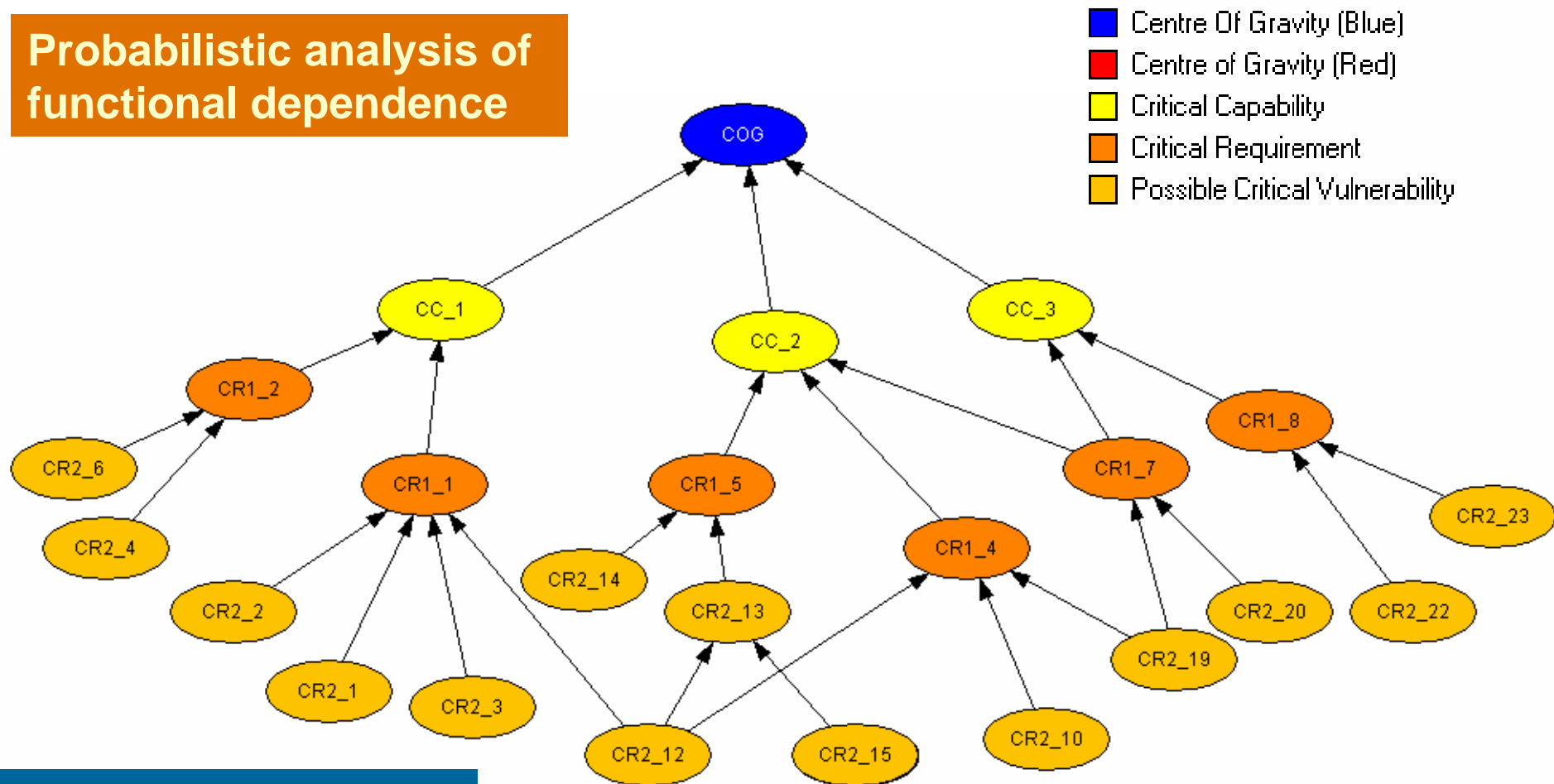
CC1 AIRLIFT	CC2 SEALIFT	CC3 AIR STRIKE	CC4 AIRBORNE	CC5 NTG
TPT a/c	TPT ship	STK a/c	ABN a/c	MFU
Crews	Naval Escort	Airfields	CAP	CAP
POL	CAP	POL	SLC	Crews
Airfields	POL	Munitions	POL	MPA
CAP		Crews	Crews	POL

Network representation of CC analysis



A Simple Example of a COG Network

Probabilistic analysis of functional dependence



Nodes represent critical capabilities or requirements and their possible strength states

The causal direction or functional dependence is represented by the direction of the arcs in the graph

COGNET at a glance

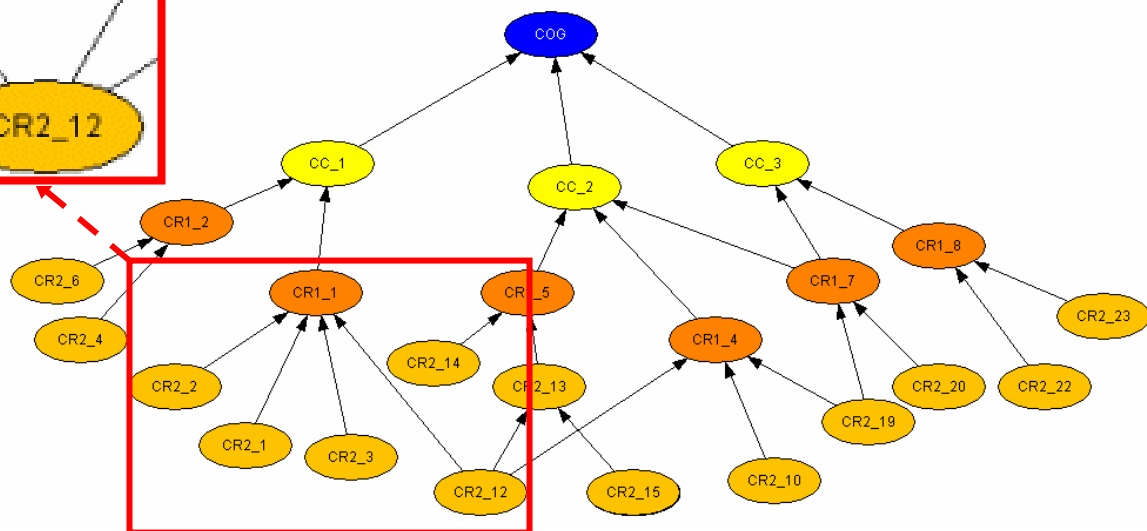
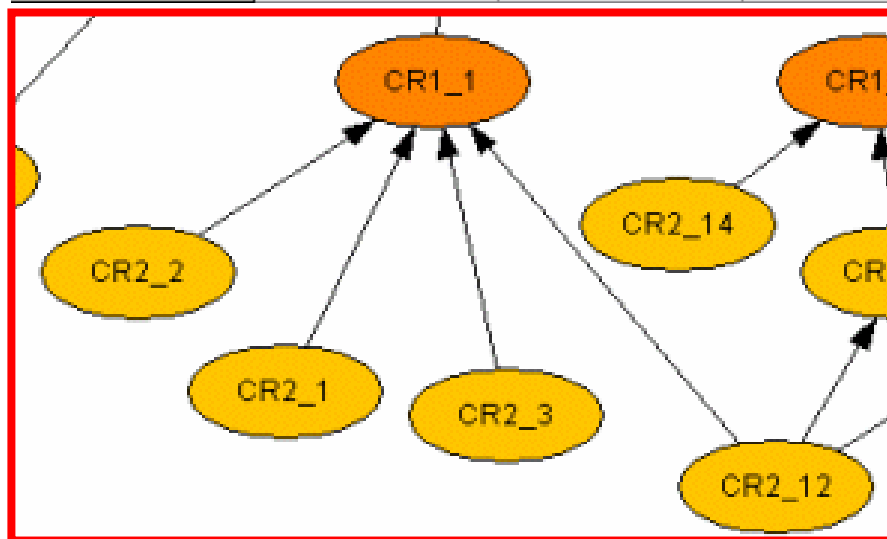
- Probabilistic modelling techniques in the form of Bayesian networks can be applied to aid the construction and analysis of COG networks in the **COG Network Effects Tool**
- COGNET captures the COG/CC/CR/CV relationship structure in a causal network
- It provides the ability to define desired effects in terms of influence on the COG
- COGNET comprises templates and generic models that are developed for frequently used Centres of Gravity
- Effects-based analysis tool.

Reasoning under uncertainty

- The numbers required for a Bayesian network are normally elicited from a domain expert - they may be completely subjective estimates of the likelihood of an event.
 - There are no historical data from which these probabilities can be determined and conducting realistic trials for the purpose of collecting this type of data is impractical. Since this alternative is not available probabilities are assigned on the basis of experience, beliefs and intuition. The subjective approach capitalises on the experience of subject matter experts.
- However, in Bayesian formalism the measures must obey the fundamental axioms of probability theory - this allows us to determine whether the model is complete and consistent.
- Determining context-dependent probabilities is much more compatible with human reasoning than estimating absolute probabilities.
 - Example: In “the probability of A given B”, B serves as a context of the belief attributed to A and is much easier to determine than “the probability of A and B”.

Conditional Probability Tables

CR2_12	Strong						
CR2_3	Strong				Weak		
CR2_1	Strong		Weak		Strong		
CR2_2	Strong	Weak	Strong	Weak	Strong	Weak	Str
Strong	0.95	0.92153	0.94632	0.85123	0.87649	0.82197	
Weak	0.05	0.07847	0.05468	0.14877	0.12351	0.17803	



Generic models: A modular representation framework

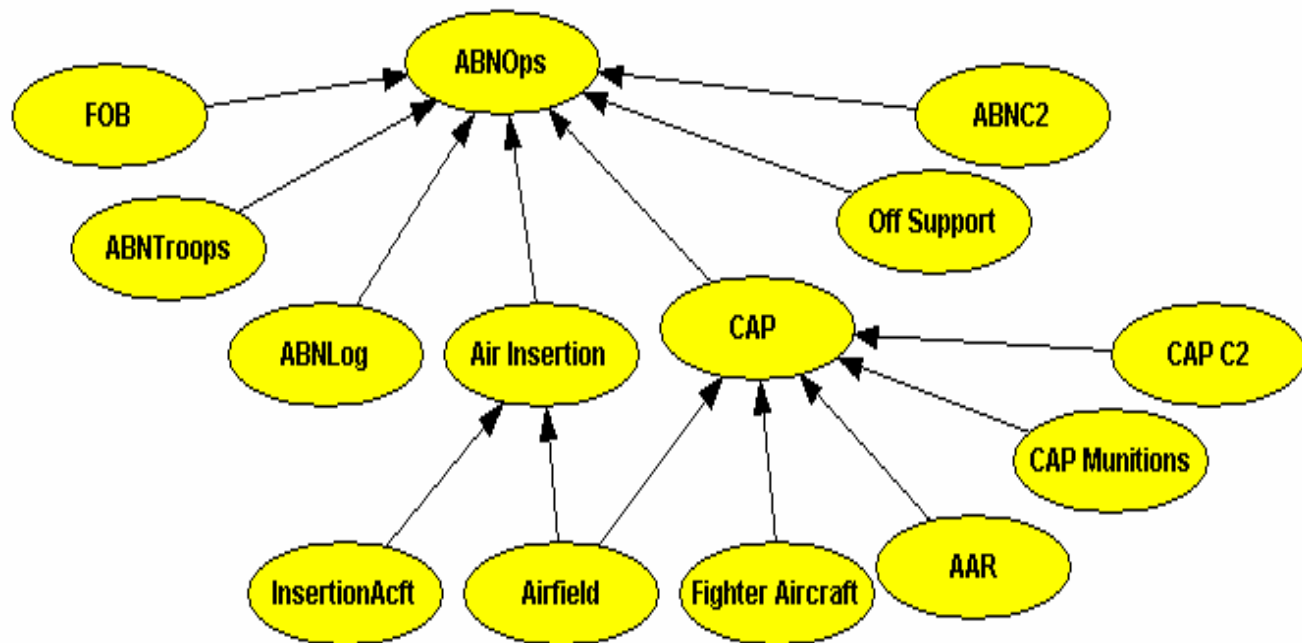
For a particular enemy:

- The centre of gravity might change according to circumstance or type of conflict.
- The current force structure and capabilities can be reflected by a relatively fixed causal network over a fixed set of critical capabilities depending on a fixed set of requirements.
- The conditional probabilities may vary with respect to the specific COG being considered.

COGNET provides a framework and database structure, which can serve as a knowledge base representing generic causal relationships to aid knowledge reuse and knowledge transfer.

Generic models database

A knowledge representation framework expressing the invariant causal relationships is being constructed for each specific operational capability.



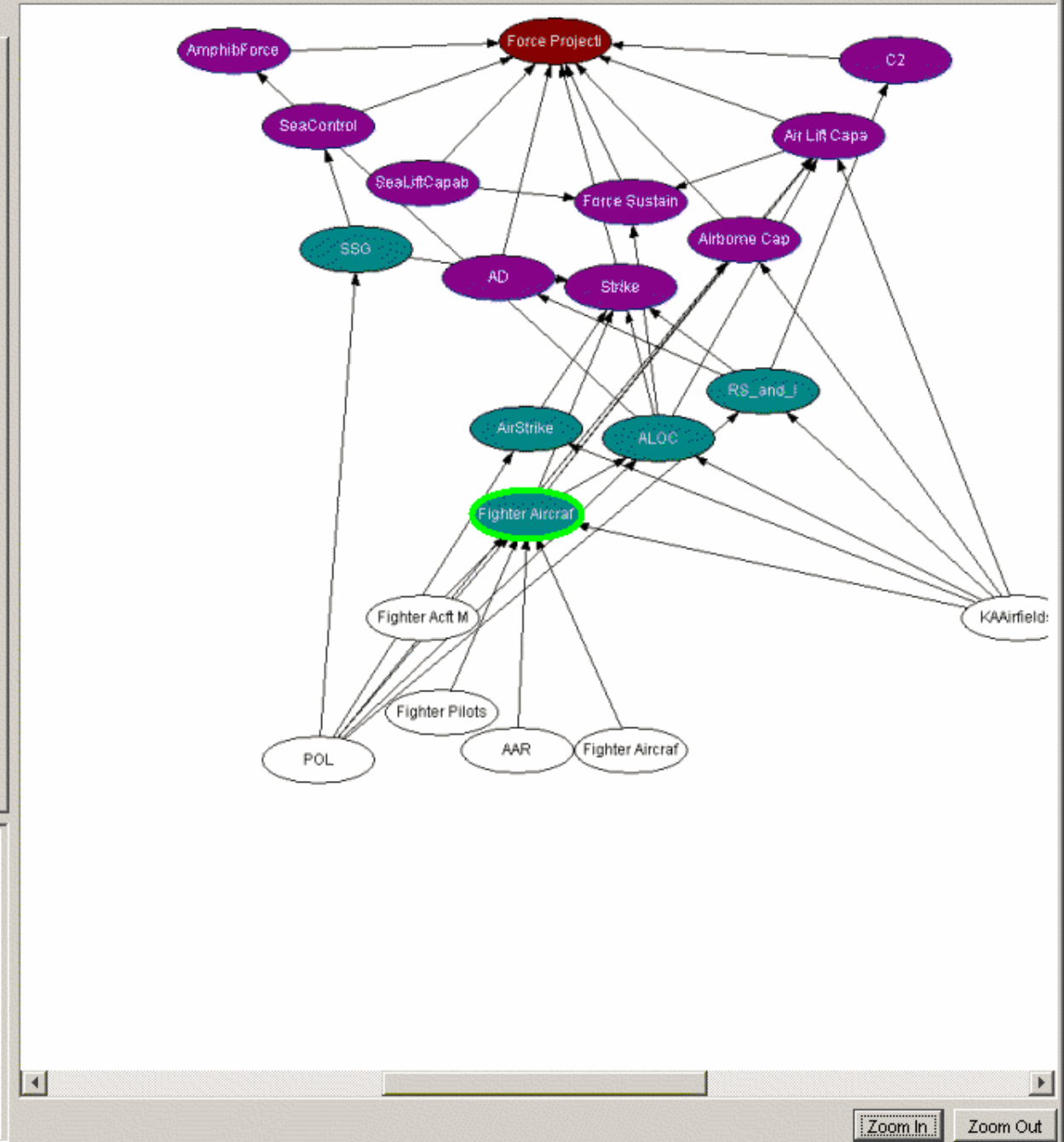
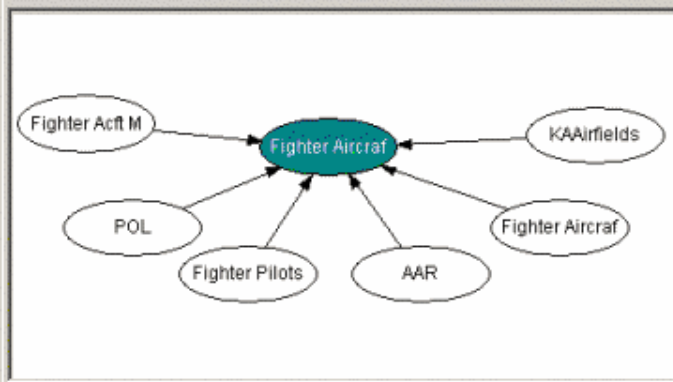
The generic framework is built on the basis of categorisation of operational-level capabilities. Model construction uses generic military categories such as Command & Control, Protection, Deployment etc and their underlying requirements, organised in hierarchies of subnetworks, which can be combined as required for each specific scenario.

This framework has been constructed in COGNET based upon a relational database system, which stores relevant entity data of capability models, ranging from standard warfare capabilities such as Battlefield Air Interdiction (BAI) to Information Operations (IO).

Network CPT Impact Analysis Nomenclature

Scenario: <Unspecified>

Country: <All>



Impact analysis

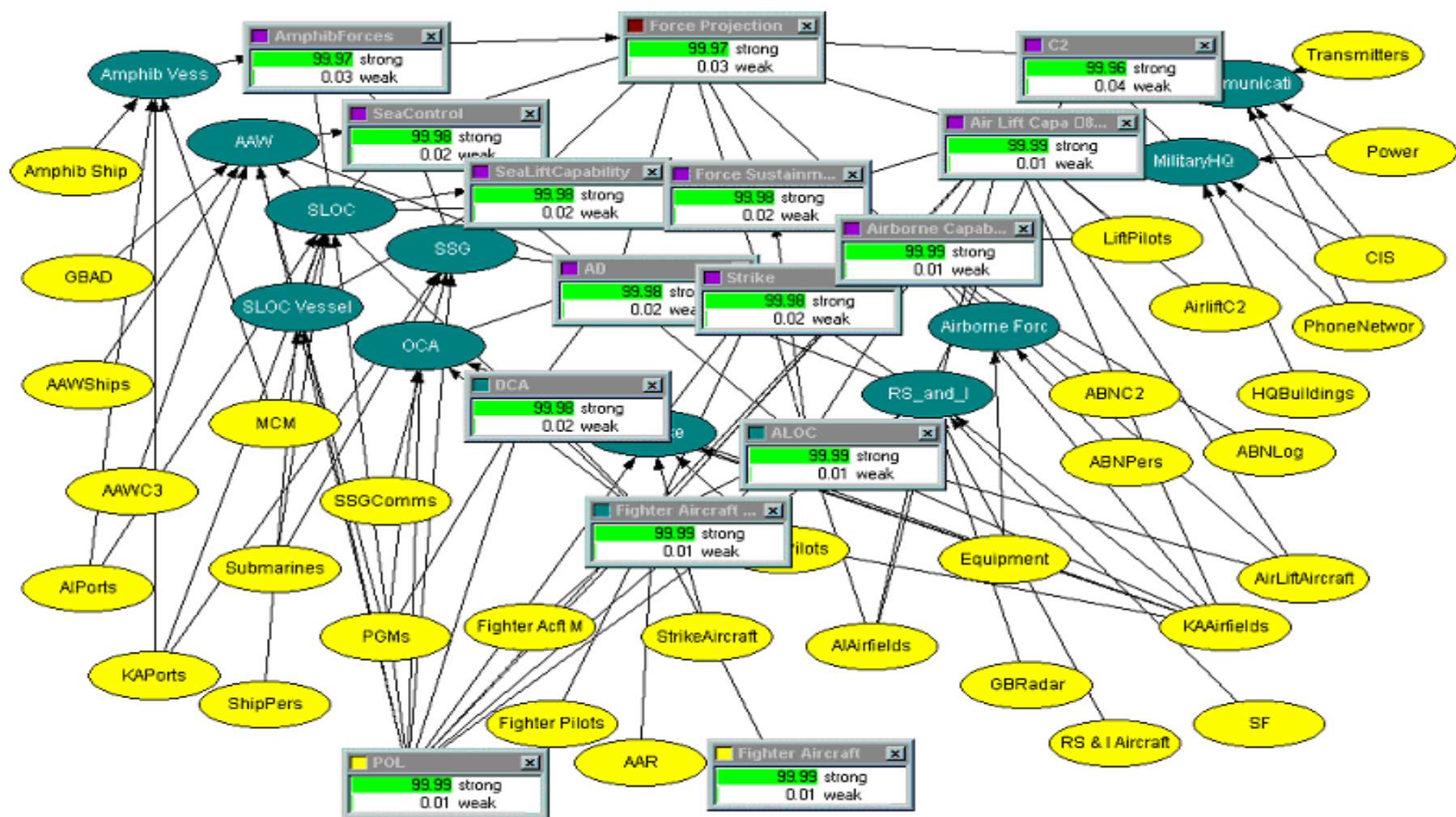
Impact analysis allows the user to investigate the potential impact that the modelled capabilities have on the enemy (or own) COG

“What if” analysis – exploratory testing for the user

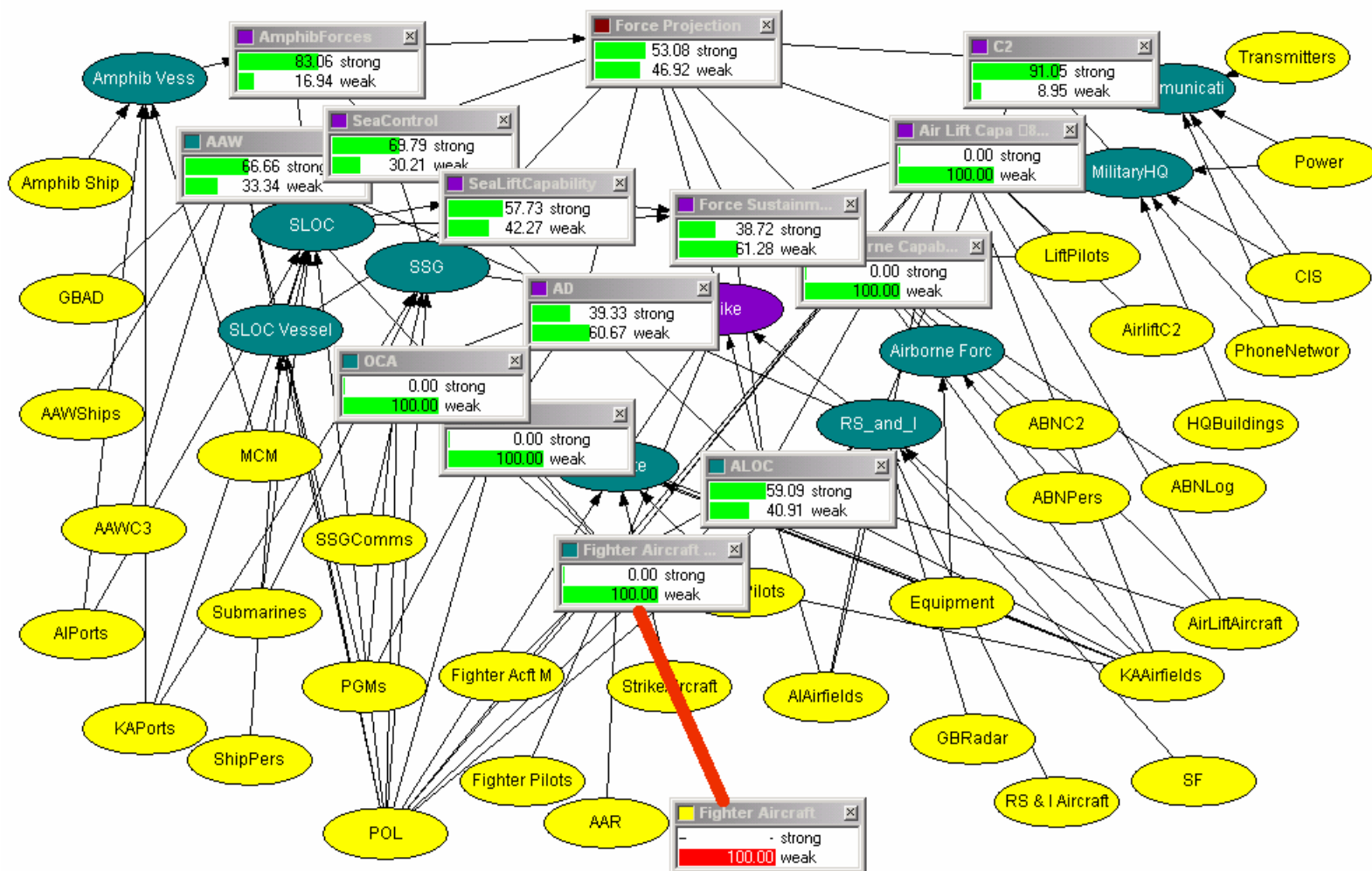
- *Base case – analysis based on prior distributions or assume all leaf nodes are in strongest state*
- *Evidence-based analysis - instantiate leaf nodes with evidence and calculate posterior distributions*
- *Relative impact – set all each leaf nodes to strongest state then change each node to weakest state in turn, compare effect on node of interest*
- *Effects-based analysis – user stipulates effect (e.g. COG strongest state probability to decrease by ~ 50%)*

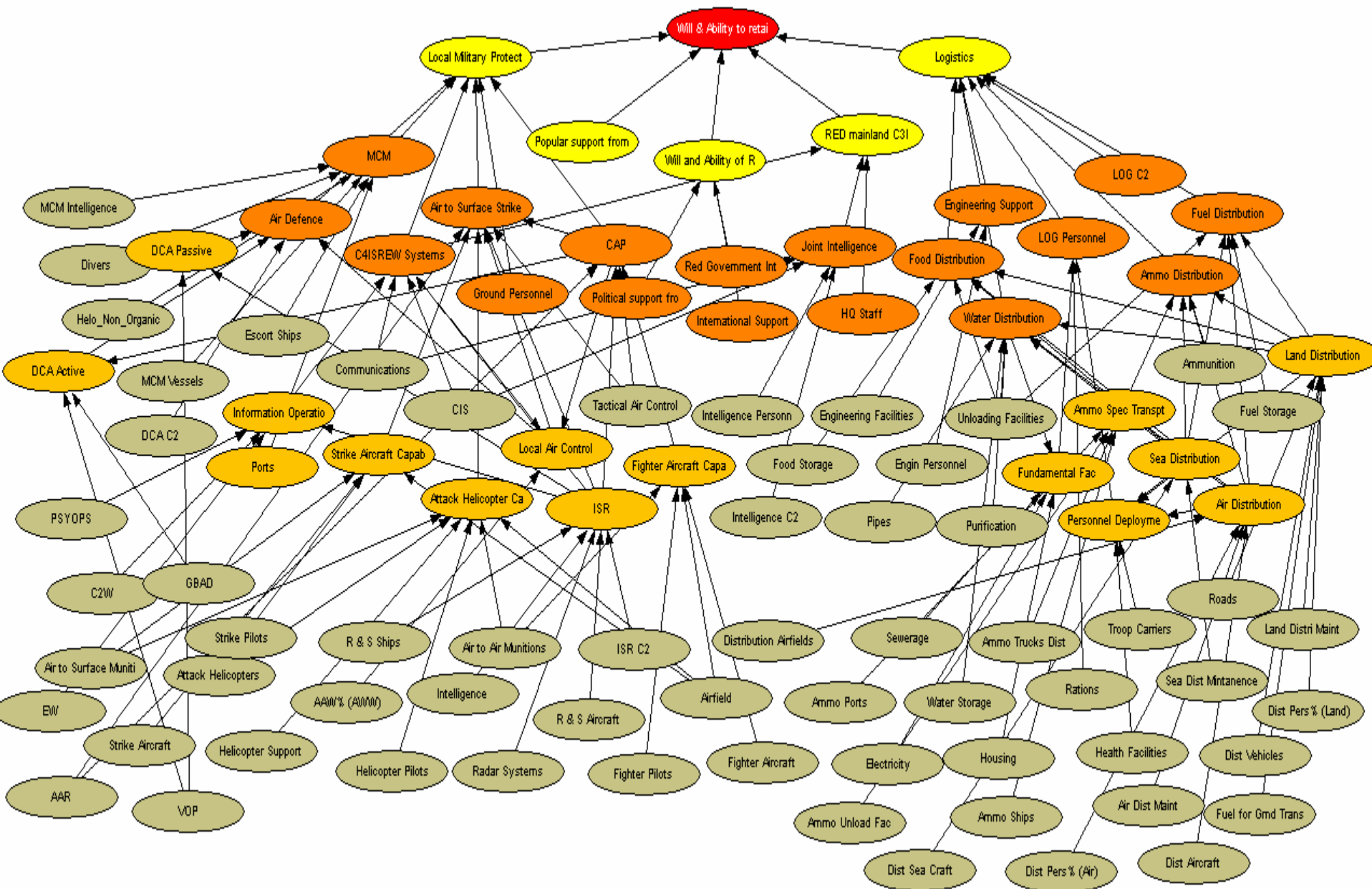
This analysis has been automated in COGNET so that a user can generate a list of initial nodes ordered by the potential effect on the node of interest.

Base case for analysis



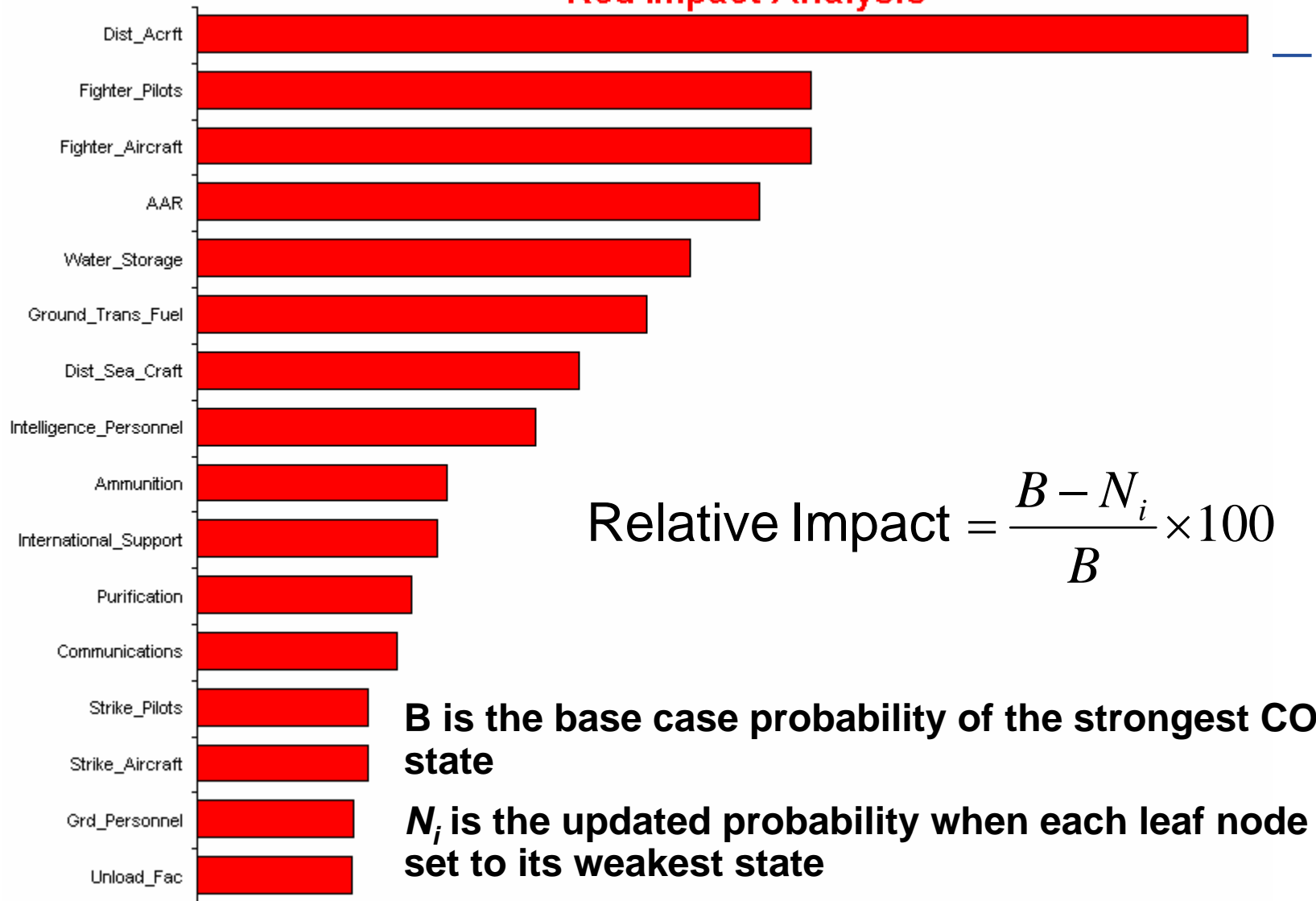
“What if?” Analysis







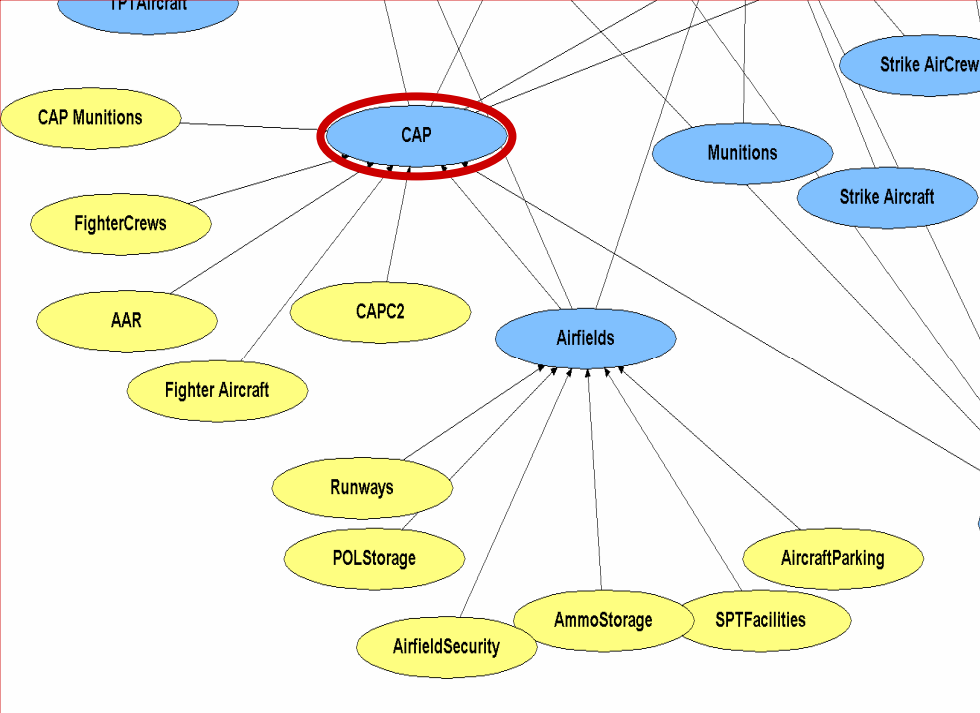
Red Impact Analysis



$$\text{Relative Impact} = \frac{B - N_i}{B} \times 100$$

B is the base case probability of the strongest COG state

N_i is the updated probability when each leaf node *i* is set to its weakest state



CAP is dependent on five parent nodes. If each of these nodes has three possible states (Strong, Degraded and Unavailable), then 243 conditional probabilities must be specified for the likelihoods associated with CAP.

- Nodes with more parents, and possibly more states, require more subjective probabilities.
- Resulting in high *cognitive load* and requiring a considerable amount of time.
- Several conditional probability table (CPT) generation algorithms are being investigated for use in COGNET.

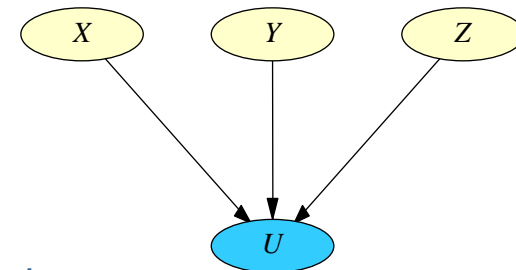
One such algorithm has so far been implemented.

The CPT generation tool – weighted sum algorithm

$$P_{y_j} = \begin{pmatrix} p_{y_j}(u_1) \\ p_{y_j}(u_2) \\ \cdot \\ \cdot \\ p_{y_j}(u_s) \end{pmatrix}$$

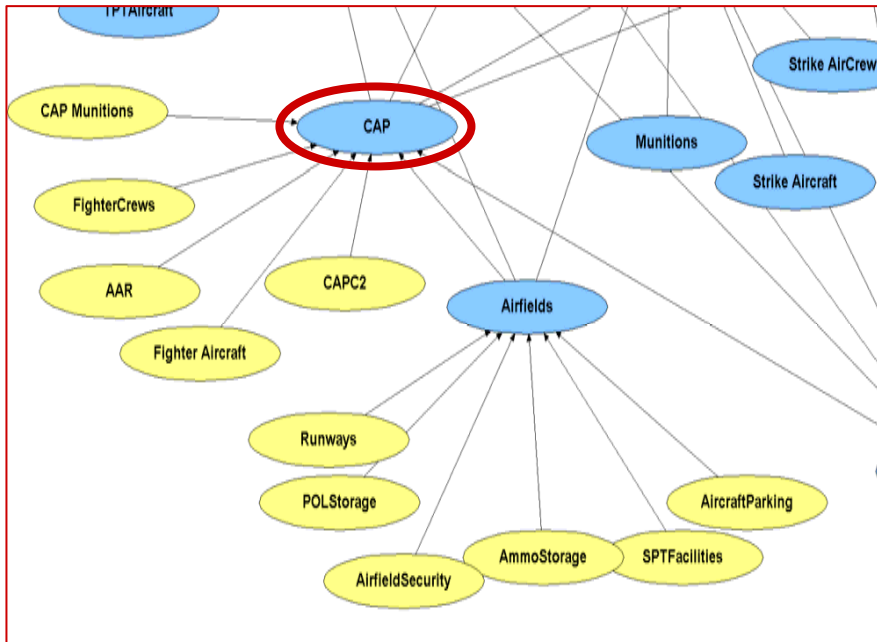
is the probability distribution matrix of the states of node U, given its parent node, Y is in state j.

λ, μ, ν are the normalised weights representing the intensities of their influence on U, which are assigned subjectively.



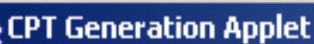
$$\begin{pmatrix} p(u_1 / x_i, y_j, z_k) \\ p(u_2 / x_i, y_j, z_k) \\ \cdot \\ \cdot \\ p(u_s / x_i, y_j, z_k) \end{pmatrix} = \lambda \begin{pmatrix} p_{x_i}(u_1) \\ p_{x_i}(u_2) \\ \cdot \\ \cdot \\ p_{x_i}(u_s) \end{pmatrix} + \mu \begin{pmatrix} p_{y_j}(u_1) \\ p_{y_j}(u_2) \\ \cdot \\ \cdot \\ p_{y_j}(u_s) \end{pmatrix} + \nu \begin{pmatrix} p_{z_k}(u_1) \\ p_{z_k}(u_2) \\ \cdot \\ \cdot \\ p_{z_k}(u_s) \end{pmatrix}$$

The CPT generation tool – critical parent nodes



The user specifies whether a parent node is critical to the capability.

A parent node is defined to be critical to a capability if the latter is totally dependent on it. In this example AAR is not considered to be critical to the CAP capability, but Fighter Aircraft Capability is.



Browse ...

Load

Weightings

Criticalities

Matrices

AAR

100

AEW and C

80

Fighter Air...

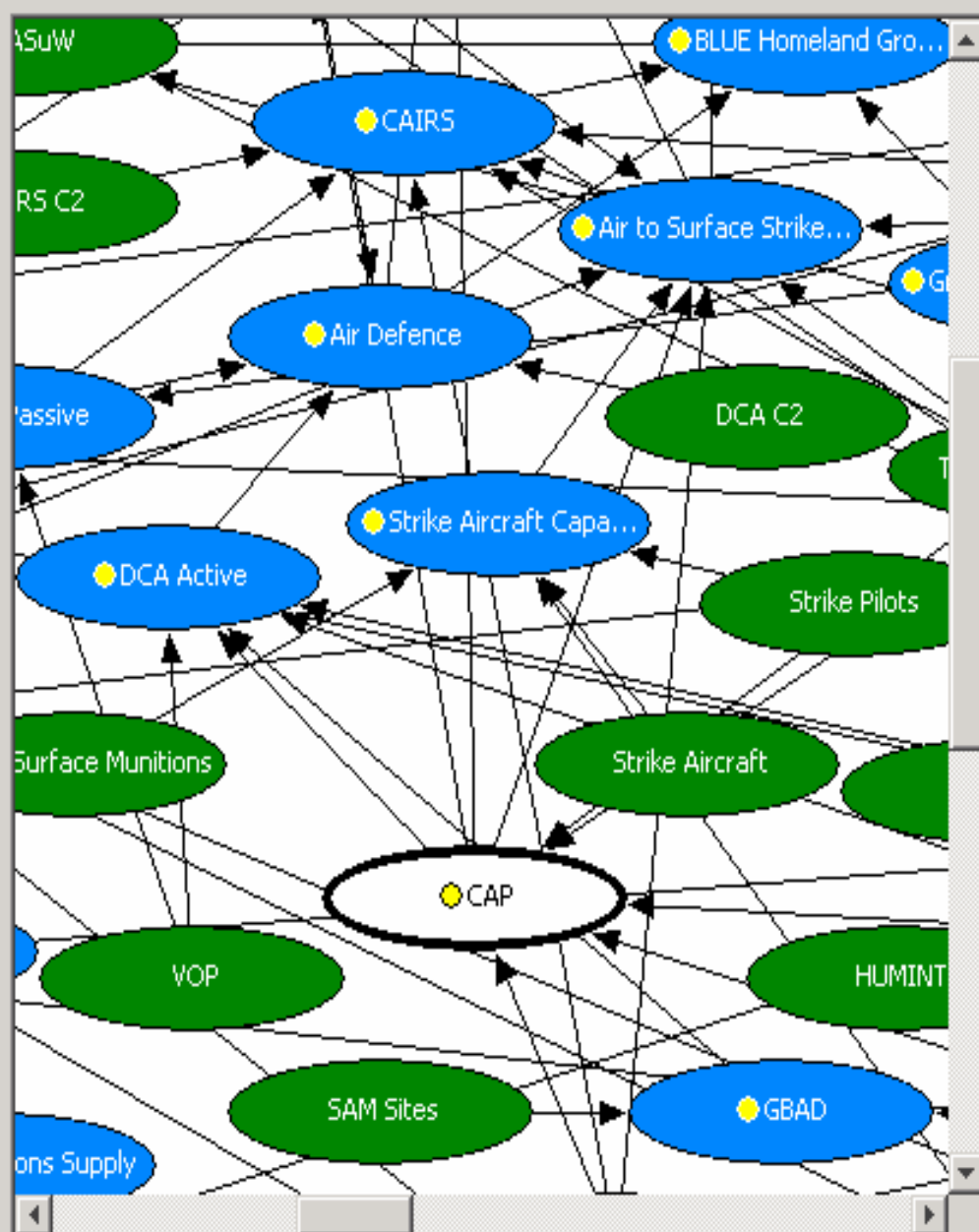
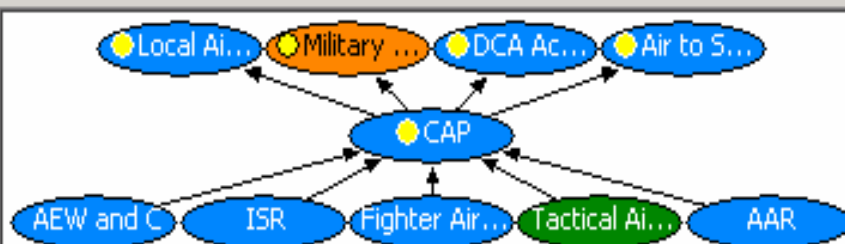
100

ISR

80

Tactical Air...

30

☒ Populated 13/2/2003☐ Checked 16/6/2003

Generate

Save

Zoom In

Zoom Out

Sensitivity analysis

- **Sensitivity analysis**: “an *informal* process of altering assumptions according to researcher intuition with the objective of determining the extent to which these changes modify the posterior distribution”.
- In contrast, “**robustness evaluation** is the *systematic* process of determining the degree to which posterior inferences are affected by both potential misspecification of the prior and influential data points”.
- Using this definition, our model verification tool can be categorized as a sensitivity analysis tool, designed to enable the user to verify that analysis results match their knowledge of the environment being modelled.

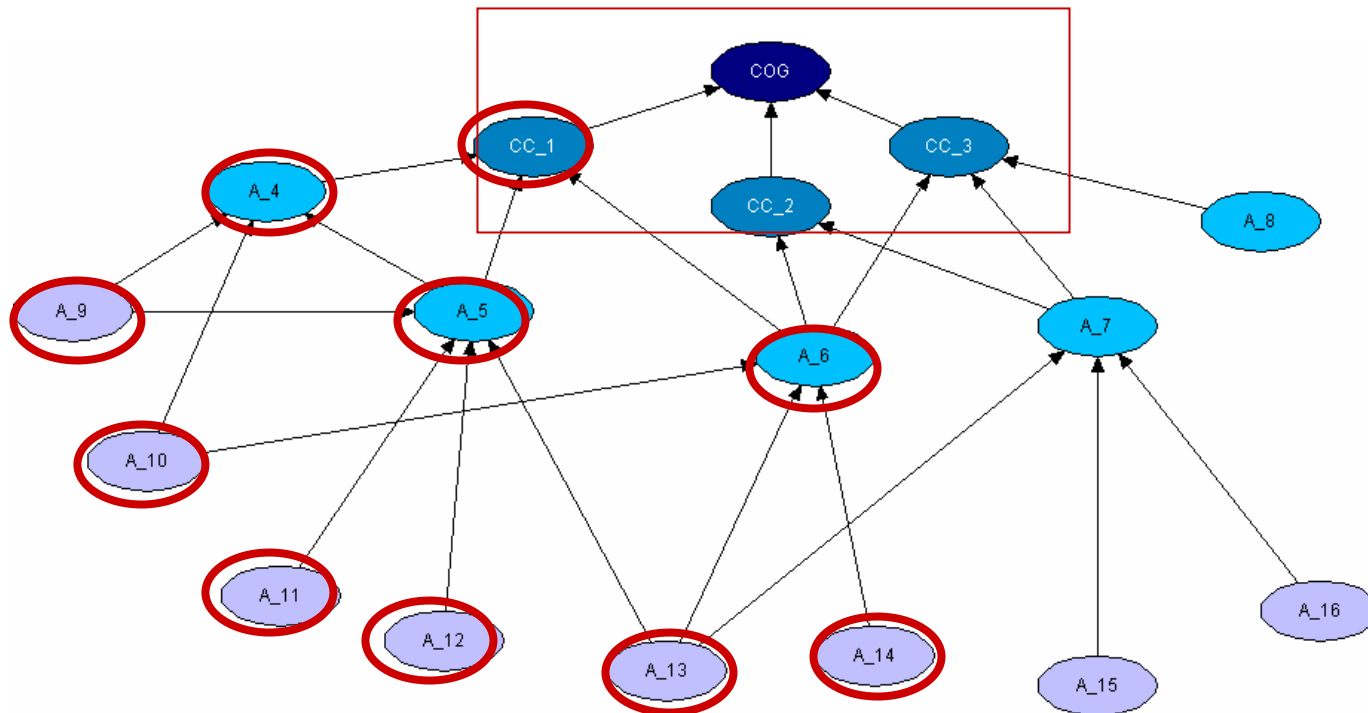
Model verification

- Model verification is invoked through the model population tool.
- The user steps through the model, fragment by fragment (a child node and its parents).
- Once population of the fragment has been finalised the model verification tool can be invoked. This involves performing importance analysis on the fragment with the node of interest set as the child node.
- Iterative refining of the weights, dependency matrices, critical node information or conditional probability table entries of the child node is pursued until the model verification output is satisfactory.

Compiling large and complex networks

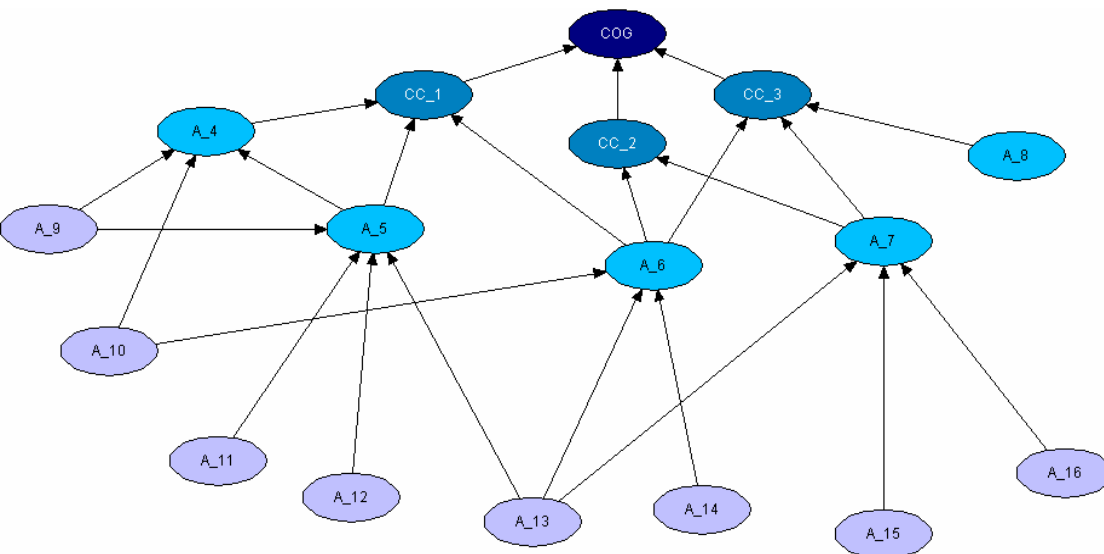
- The integration of generic subnets into a COGNET model make them comprehensive but very large and complex.
- Although there is no problem with compiling large two-state networks we have recently started converting our models to three-state nodes. The exponential increase in memory requirement has meant that some of our more comprehensive networks cannot be compiled.
- Looking at the structure of most COGNET models it is not difficult to understand why: many of the nodes have 5 or 6 parents and quite a few of these parent nodes have several children. In larger, denser networks, nodes are less likely to be adjacent to simplicial nodes and end up as members of very large cliques once the graph is triangulated.
- Fortunately there is a way to exploit the structure of COGNET models to make compilation of large three-state networks possible [provided we're only interested in forward propagation].

Exploiting the structure of COGNET models



The **structure** of typical COGNET networks is such that they can be separated into independent sub-networks that can be compiled sequentially.

Exploiting the structure of COGNET models



From the definition of Causal Bayesian Networks [Pearl], since the **underlying relationships are causal** we can represent external or spontaneous changes as follows:

Suppose we wish to investigate how neutralising the critical requirement represented by an intermediate node A_7 impacts on the COG.

We represent this in the network by instantiating A_7 with this evidence and deleting the links from A_7's parents to it, thus turning A_7 into a leaf node.

By doing so we are reflecting the fact that since we know the state of A_7 we are no longer interested in the effect other nodes might have on it.

We propagate this evidence through the rest of the network to see the effect on the nodes of interest, typically the COG.

Conclusion

- The network representation facilitates reasoning and enhances shared understanding of complex situations.
- Probabilistic models ensure that uncertainties and subjective judgements are clearly represented.
- Generic models database enables future re-use and traceability.
- CPT generation, impact analysis and model checking tools have been specially designed for military users, whose expertise is in the system being modelled rather than the underlying mathematics.